Construction of a Fully Active Inner Detector for MINERvA

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The NuMI beamline, which will be the world's highest intensity neutrino beam for many years after commissioning in early 2005, offers the particle and nuclear physics communities a new opportunity. By constructing a fully active detector to run for the first time in a high rate neutrino beam, the MINERνA experiment proposes to exploit this opportunity to access a broad and rich program in neutrino scattering physics.

The MINERνA physics program consists of high rate studies of exclusive final states in neutrino scattering, of the connection between perturbative QCD and the non-perturbative regime, and of studies of the axial current in the elastic, DIS and off-forward regimes, as well its modification in the nuclear environment. MINERνA then seeks the application of its data to aid present and future neutrino oscillation experiments, where understanding the details of neutrino cross-sections and final states is essential for separating backgrounds to oscillation from signal. The importance of this application was recently stressed in the APS Multidivisional Neutrino Study report. This report predicated its recommendations on a set of "assumptions" about the current and future program, including

> *"determination of the neutrino reaction and production cross sections required for a precise understanding of neutrino-oscillation physics and the neutrino astronomy of astrophysical and cosmological sources. Our broad and exacting program of neutrino physics is built upon precise knowledge of how neutrinos interact with matter."*

MINERνA can address these topics with a low-risk detector of modest cost. The performance of this detector will be excellent for resolving exclusive processes and for measuring kinematics in inclusive reactions.

The MINERνA collaboration currently consists of 58 nuclear and particle physicists from 13 universities in four countries and two US national laboratories (FNAL and Jefferson Lab). The subset of University groups represented in this proposal have a strong record of training graduate and undergraduate students and post-doctoral physicists in experiments of the FNAL neutrino program (Rochester, William & Mary) and the Jefferson Lab Hall A and Hall C programs (Hampton). To build on this record, we propose a program of education and public outreach activities associated with the construction and physics of MINERνA.

<u>MINERνA, Fermilab and this Proposal:</u> MINERνA received Stage I approval from Fermilab in April 2004. As detailed in the accompanying Letter of Support, the host laboratory has undertaken to provide significant technical, in-kind, and financial resources essential to the success of the project during construction and operation. FNAL is committed to run the NuMI beam through at least 2009, and other proposals for the more distant future are under active consideration by the lab. We therefore anticipate a long-term physics program, perhaps spanning up to a decade.

This proposal requests support for the collaborating university groups to construct the inner detector scintillator planes and associated optical cables, the critical path items in the construction plan for the entire MINERνA detector during the period from June 2005 until June 2007. Supported by existing operating funds and Fermilab, MINERνA has already demonstrated the design and function of these inner detector planes with a vertical slice test. The funds requested in this proposal will allow the University collaborators to purchase materials and equipment and employ the technical staffs necessary to construct the inner detector, in collaboration with Fermilab staff.

This proposal can only fund a portion of the MINERνA construction. Funds for the balance of the MINERνA experiment are being sought from other sources. Although we propose a specific time-line for construction of the inner detector in this proposal, we would expect that the release of funds from this proposal, if approved, would remain contingent on the completion of a funding package for the entire experiment, as signified by Stage II approval of MINERνA by Fermilab.

1 Research Activites: The MINERνA Physics Program

MINERνA [1] offers a unique opportunity to explore a broad spectrum of physics topics; some have never been studied systematically, while others are plagued by sparse data with large statistical and systematic errors. The high-statistics studies listed below are important for both the particle and nuclear physics communities, providing information complementary to JLab charged lepton studies in the same kinematic range:

- Precision measurement of the quasi-elastic neutrino–nucleus cross-section, including its E_ν and q^2 dependence, and study of the nucleon axial form factors. Over **300 K** events are expected in the fiducial volume during a four-year MINERνA run.
- Determination of cross-sections in the resonance-dominated region for both neutral-current (NC) and charged-current (CC) interactions, including study of isospin amplitudes, measurement of pion angular distributions, isolation of dominant form factors, and measurement of the effective axial mass. A total of **470 K** one- and two-pion events make up the resonance sample.
- Precision measurement of coherent single-pion production cross-sections, with particular attention to target A-dependence. NC coherent pion production is a significant background for next-generation of neutrino oscillation experiments probing $\nu_\mu \rightarrow \nu_e$ oscillation. A sample of **20 K** CC events is expected off carbon. The expected NC sample is roughly half the CC sample.
- Examination of nuclear effects in neutrino interactions, including final-state modifications in heavy nuclei, by employing carbon, iron and lead targets. These effects play a significant role in neutrino oscillation experiments measuring ν_μ disappearance as a function of E_ν. It has recently been suggested that, for a given Q^2, shadowing can occur at much lower energy transfer (ν) for neutrinos than for charged leptons. This effect is unaccounted for in neutrino event generators. With sufficient $\overline{\nu}$ running, a study of flavor-dependent nuclear effects can also be performed. Due to the different mix of quark flavors, this is another way in which neutrino and charged-lepton nuclear effects differ. MINERνA will collect over **700 K** CC events off both iron and lead, in addition to the carbon sample.
- Study of nuclear effects on $\sin^2\theta_W$ measurements, and the NC/CC ratio for different nuclear targets.
- Exploration of the W (hadronic mass) transition region where resonance production merges with deep-inelastic scattering (DIS), testing phenomenological models like quark/hadron duality. A sample of **500 K** multi-pion events is expected with W $\leq$ 2.0 GeV.
- With a sample of over **1 M** CC DIS events, a much-improved measurement of the parton distribution functions, particularly at large x_{Bj}, will be possible using a measurement of all three ν structure functions. Although we expect over **100 K** CC $\overline{\nu}$ events in the four year MINERνA ν run, an additional dedicated $\overline{\nu}$ run would be required to measure the three $\overline{\nu}$ structure functions with similar precision.
- Examination of the leading exponential contributions of perturbative QCD.
- With nearly **50 K** fully reconstructed exclusive events[2], precision measurement of exclusive strange-production channels near threshold. This will significantly improve our knowledge of backgrounds in nucleon-decay searches. Also, determination of V_{us}, and searches for strangeness-changing neutral-currents and candidate pentaquark resonances will be undertaken. Measurement of hyperon-production cross-sections, including hyperon polarization, is feasible with exposure of MINERνA to $\overline{\nu}$ beams.
- Improved determination of the effective charm-quark mass (m_c) near threshold, and new measurements of V_{cd}, $s(x)$ and, independently, $\overline{s}(x)$.

These are worthy research topics in their own right, and improved knowledge in most is essential to minimizing systematic uncertainties in neutrino-oscillation experiments. The remainder of this section provides more detail, and illustrates the rich physics potential of MINERνA.

1.1 Low-energy Neutrino Cross-sections: Quasi-elastic Scattering

CC quasi-elastic reactions play a crucial role in non-accelerator and accelerator neutrino oscillation studies. Cross-section uncertainties - often expressed as uncertainty in the axial-vector mass - are a significant contribution to the errors of these experiments. Available measurements of this cross-section are clustered below E_ν = 5 GeV with a few isolated measurements out to 12 GeV. The measurements have statistical errors of 10–15%, plus another 10–20% flux systematic error. A full simulated analysis of the quasi-elastic channel in MINERνA has been carried out [3]. The efficiency and purity of the final sample are Q^2 dependent, but the average efficiency was 74% with a purity of 77%. The resulting fit is shown in Figure 1. MINERνA will measure the cross-section up to E_ν = 20 GeV with statistical errors ranging from $\leq$ 1% at low E_ν up to 7 % at E_ν = 20 GeV. The expected beam systematic error is 4–6% thanks to precision measurements of hadron production (the largest uncertainty in predicting neutrino flux) by the current MIPP experiment [4].

Despite recent advances in measurement of the vector component of elastic scattering at SLAC and JLab [5], there is still an uncertainty in the large Q^2 behavior of G_E^p: experimental results differ, depending on whether the analysis is based on cross-section or polarization techniques. For the axial-vector component of this channel, measurement of neutrino quasi-elastic scattering is the most direct way to improve our knowledge. MINERνA's ability to measure $d\sigma/dQ^2$ to high Q^2 not only allows investigation of the non-dipole component of the axial-vector form factor to an unprecedented accuracy, but also permits discrimination between the two alternative high Q^2 behaviors mentioned above. Figure 1 shows the extraction of the axial-vector form factor from the quasi-elastic event sample accumulated over a 4-year MINERνA run. The data points are plotted as a ratio of F_A/F_A(Dipole) with the indicated assumptions. Also shown are the currently available values of F_A from early experiments. MINERνA can measure the axial nucleon form-factor with precision comparable to vector form-factor measurements at JLab. Combining MINERνA's measurements with present and future Jefferson Lab data will permit precision extraction of all form factors needed to improve and test models of the nucleon.

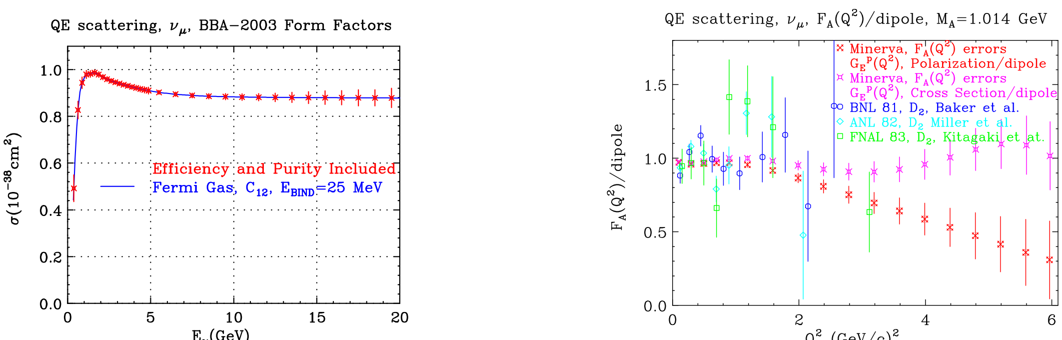


Figure 1: At left is the simulated cross-section measurement for MINERνA in a 4-year run (statistical errors only) assuming M_A=1.00 GeV and the Fermi gas model. At right are the projected axial form-factor results for MINERνA for two different assumptions: F_A/dipole=G_E^p/dipole from cross-section and F_A/dipole=G_E^p/dipole from polarization. Also shown are the extracted values of $F_A(q^2)$/dipole for deuterium bubble chamber experiments Baker *et al.* [6], Kitagaki *et al.* [7] and Miller *et al.* [8].

1.2 Low-energy Neutrino Cross-sections: Resonance Production

To simulate resonance-mediated reactions, Monte-Carlo programs use early theoretical predictions by Rein & Sehgal [9] or results from electro-production experiments, since existing data on neutrino-induced resonance production is inadequate. The theoretical and experimental picture of the resonance and transition regions is far more obscure than the quasi-elastic and DIS regions which border it. Since the event samples of present and proposed neutrino oscillation experiments fall inside this poorly-understood regime, resonant pion production is an important source of background and systematic uncertainty. This kinematic region will be carefully examined by MINERνA.

Analysis of resonance production in MINERνA[10] will focus on several experimental channels, including inclusive scattering in the resonance region ($W < 2$ GeV) and exclusive charged and neutral pion production. To date, analysis efforts have focused on MINERνA's performance for inclusive resonance production [11], particularly near the $\Delta(1232)$ resonance. This analysis indicates that the resolution on W is about 100 MeV in the region of the Δ, and the Q^2 resolution is better than 20%. Despite this resolution smearing, and distortion introduced by Fermi motion of bound nucleons in carbon, the Δ peak is still clearly visible in the reconstructed W distribution.

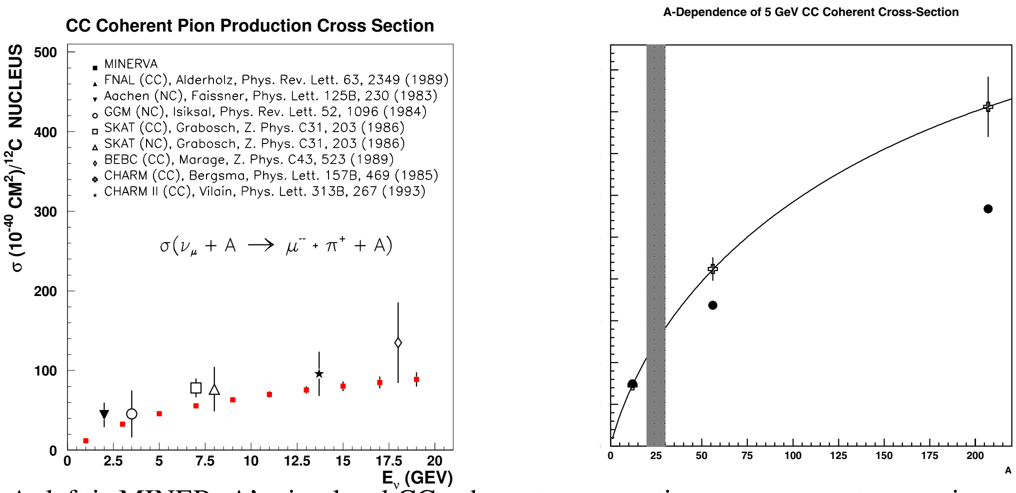


Figure 2: At left is MINERνA's simulated CC coherent cross-section measurement, assuming a 4-year run, statistical errors only, compared with published data. At right, the range of A-dependence in coherent pion-production accessible to MINERνA is compared to the narrow range of existing data, shown by the shaded band. The curve is the prediction of the Rein-Seghal model [14] while the solid circles correspond to the prediction of Paschos and Kartavtsev [15]

Analysis methods are being developed to exploit the tracking capability of MINERνA to refine the kinematic reconstruction of low-multiplicity resonant events. This will permit more accurate determination of W in the neighborhood of the Δ resonance and facilitate the exclusive analysis of resonant events.

1.3 Low-energy Neutrino Cross-sections: Coherent Pion Production

Both CC and NC coherent scattering result in a single forward-going pion with little energy transfer to the target nucleus. For neutral-currents, the forward-going π^0 can mimic an electron and be misinterpreted as a signal in ν_e appearance experiments. Existing cross-section measurements for this reaction are only accurate to 35%, at best, and only available for a limited number of target nuclei in the few–10 GeV region [12].

MINERνA, with its high statistics and variety of nuclear targets, will greatly improve our experimental understanding of coherent processes. A complete simulated analysis of the CC coherent production channel has been carried out [13]. The kinematic cuts employed reduce the background by three orders of magnitude while reducing the signal by a factor of three.

Figure 2 shows the estimated statistical precision of MINERνA's CC coherent scattering measurement, as a function of neutrino energy, after background subtraction. The model of Rein & Seghal [14] is assumed. Also plotted are the only currently available measurements in this kinematic region showing their total errors.

MINERνA's CC coherent event sample can also be used to study the differential cross-sections. Comparion of the overall rates of NC and CC production, as well as the pion energy and angular distributions will allow valuable tests of the various models. For several recent models, the predicted NC/CC ratios in coherent scattering differ by around 20% [14, 15].

MINERνA will also compare the reaction rates for lead, iron and carbon. The A dependence of the cross-section depends mainly on the assumed model of the hadron–nucleus interaction and serves as a crucial test for that component of the predictions [16]. No experiment to date has been able to perform this comparison. Figure 2 illustrates the broad range in A covered by MINERνA's measurement of the coherent pion cross-section. The shaded band is the range in A covered by existing experiments.

1.4 Nuclear Effects in Neutrino Scattering

Most neutrino scattering experiments, including neutrino oscillation experiments, require massive nuclear target/detectors to obtain useful reaction rates. Analysis of neutrino reactions with nuclear media requires understanding the nuclear environment's effect on the process [26]. There are two general categories of such nuclear effects:

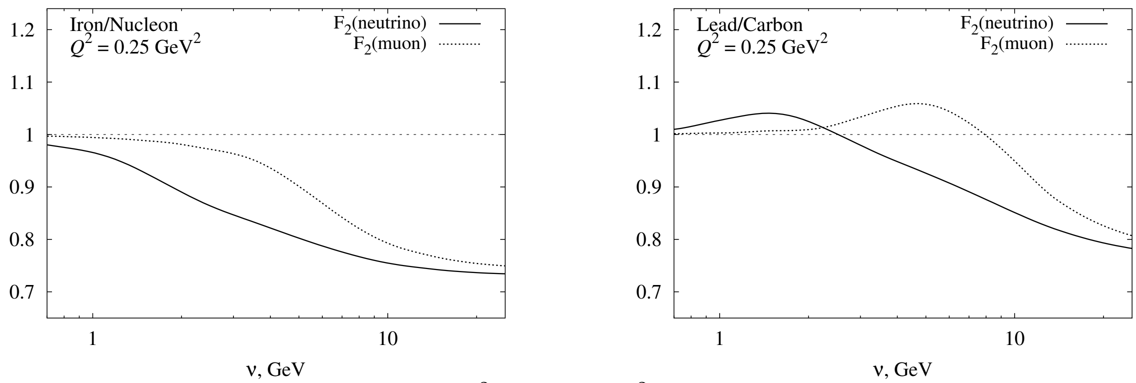


Figure 3: Predicted shadowing effects at Q^2 = 0.25 GeV^2 as a function of energy transfer (ν), for neutrinos (solid line) and muons (dotted line). The plot on the left is for iron compared to deuterium while the right plot is lead compared to carbon, what MINERνA will measure.

- The neutrino interaction probability on nuclei is modified relative to free nucleons. Nuclear effects of this type have been extensively studied in DIS structure function measurements using muon and electron beams, but have not been explored with neutrinos. Depending on the kinematic region, these nuclear effects can be quite different for neutrinos, particularly the shadowing phenomenon [25]. As explained in [28], for a given Q^2 the cross-section suppression due to shadowing occurs for much lower energy transfer (ν) in neutrino interactions than for charged leptons. Figure 3 shows the predicted difference between neutrino and charged lepton shadowing as a function of the energy transfer (ν). On the left is the ratio of iron to deuterium while on the right is shown the ratio of lead to carbon. The projected statistical error on the ratio of lead to carbon is order 2% at ν = 6 GeV. Clearly this is an important effect, and without MINERνA, there are no data available to measure it.

- Hadrons produced in a nuclear target may undergo final-state interactions (FSI), including re-scattering and absorption. These effects may significantly alter the observed final-state configuration and measured energy [29, 30], and are sizable at neutrino energies typical of current and planned oscillation experiments [27].

The hadron shower observed in neutrino experiments is actually the *convolution* of these two effects. FSI effects are dependent on the specific final states that, even for free protons, differ for neutrino and charged-lepton reactions. The suppression or enhancement of particular final states by nuclear effects also differ for neutrino and charged lepton reactions. For these reasons, measurements of nuclear effects with charged leptons cannot be simply applied to neutrino-nucleus interactions.

To study these questions in MINERνA, carbon, iron and lead targets will be installed upstream of the pure scintillator active detector. To measure the overall effect [26] of the nucleus, the observed hadron energy and multiplicity will be measured for all three targets as a function of muon variables to determine an (A,p_μ) correction factor to the visible hadron energy of CC events.

1.5 The Perturbative - Non-Perturbative Interface and Deep-Inelastic Scattering

Three decades after establishment of QCD as the theory of the strong interaction, understanding *how* QCD works remains one of the great challenges in elementary particle and nuclear physics. A major obstacle arises because the degrees of freedom observed in nature (hadrons and nuclei) are totally different from those appearing in the QCD Lagrangian (current quarks and gluons). Making the transition from quark and gluon to hadron degrees of freedom is therefore the key to our ability to describe nature from first principles.

Despite the apparent dichotomy between the partonic and hadronic regimes, in nature there exist instances where the low-energy behavior of cross-sections (averaged over appropriate energy intervals) closely resembles that at asymptotically high energies, calculated in terms of quark-gluon degrees of freedom. This phenomenon is referred to as *quark-hadron duality* and is the focus of substantial recent interest in probing the structure of the nucleon [18, 19, 20, 21, 22]. For example, there are over 10 related experiments at JLab.

Understanding this transition requires reliable data in three kinematic regimes: in the scaling domain of high Q^2 DIS scattering; in the hadronic region of resonances and quasi-elastic scattering; and, perhaps most importantly, in the moderate Q^2 region between the two, where the transition is most dramatically manifest. MINERνA is uniquely situated to address this compelling topic for the first time with neutrinos and measurements spanning all three regimes, providing reliable data in the crucial transition region [17].

Weak currents provide complementary information on the quark structure of hadrons, inaccessible to electromagnetic probes. Although a duality should also exist for weak structure functions [23], the details of how this duality is manifested in neutrino scattering may be quite different from that observed in electron scattering. MINERνA, specifically designed to measure low-energy neutrino-nucleus interactions accurately over the resonance and DIS regimes, is an exceptional tool for study of duality with the weak current [24].

Once in the perturbative QCD regime, the evolution of parton distribution functions (pdf's) takes high-x_{Bj} pdf's at low Q^2 and evolves them down to moderate-and-low x at higher Q^2. This means that one of the larger contributions to background uncertainties in, for instance, LHC measurements, will be the very poorly-known high-x pdf's at the lower Q^2 values accessible to the NuMI beam. MINERνA will run in the optimal kinematic region and will yield the statistics necessary to begin addressing this important concern.

Finally, it is important to note that the moments of structure functions are a subject of attention in lattice QCD simulations. Comparisons of the experimental moments with those calculated on the lattice over a range $Q^2 \approx$ 1–10 GeV^2 will allow one to determine the size of higher twist corrections and the role played by quark-gluon correlations in the nucleon. For the experimental moments, an appreciable fraction of the strength resides in the nucleon resonance region. Therefore, while a broad range in x is required at fixed Q^2 values to obtain the moments, precise resonance region data are imperative. Moreover, lattice calculations are in moments of pdf's as well as structure functions, requiring flavor decomposition. For all of these reasons, MINERνA will also provide a vital comparison with results from lattice QCD.

1.6 Impact of MINERνA's Results on Neutrino Oscillation Studies

The MINERνA study of nuclear effects and low-energy neutrino cross-sections has direct and important applications to neutrino oscillation experiments such as the MINOS ν_μ disappearance experiment and the future T2K and proposed NOνA ν_e appearance searches.

For MINOS the final observed energy may be significantly lower than the incoming neutrino energy [29, 30]. Since determination of Δm^2 depends on knowledge of the *initial* E$_\nu$, understanding this energy distortion is crucial for a precise Δm^2 determination. For T2K and NOνA, knowledge of the coherent and resonant π^0 background as well as the signal processes are essential. To better understand how MINERνA's results would improve neutrino oscillation experiments, a preliminary quantitative study [31] has been performed.

Figure 4 summarizes two results from this study. The left plot shows the statistical error for the MINOS Δm^2_{23} measurement as a function of Δm^2, as well as the systematic uncertainty assuming the current unsatisfactory knowlege of nuclear effects in neutrino reactions subject to pion absorption and rescattering in the nucleus. The right plot shows the statistical and systematic error on $\sin^2 2\theta_{13}$ for NOνA as a function of $\sin^2 2\theta_{13}$. In both plots two different systematic uncertainties are shown: one assuming the current cross-section uncertainties, the other assuming the reduced uncertainties expected as a result of MINERνA.

Even these preliminary studies illustrate clearly how MINERνA will play a key role in allowing current and future precision oscillation experiments reach their ultimate sensitivity. To obtain the most precise value of Δm^2_{23} (which is eventually required to extract mixing angles and the CP-violating phase) we must better understand and quantify the nuclear processes interposed between the interaction of an incoming neutrino and measurement of outgoing particles in the detector. Extracting mixing parameters such as θ_{13}, and ultimately the neutrino mass hierarchy and CP phase, also requires much better understanding of resonant and coherent cross-sections. Precision measurement of nuclear effects and exclusive cross-sections will provide the necessary foundation for the future study of neutrino oscillation with high-luminosity beams whose unprecedented statistical power will otherwise be compromised by systematic uncertainties.

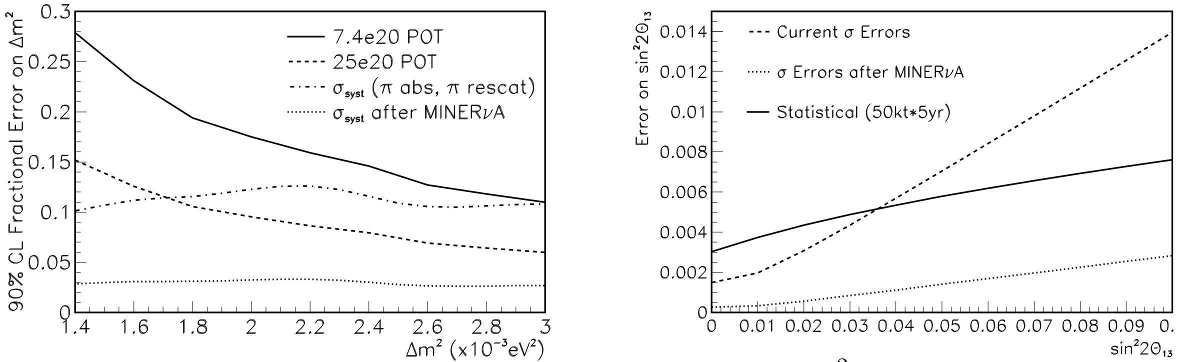


Figure 4: Left: Fractional size of the 90% confidence level region at $\sin^2 2\theta_{23} = 1$, assuming the uncertainties for nuclear effects are those described in the text, and a 0.5 GeV muon momentum cut. Right: Statistical error, current cross-section systematic errors, and post-minerva cross-section systematic uncertainties in a NOνA measurement of $\sin^2 2\theta_{13}$, as a function of $\sin^2 2\theta_{13}$.

1.7 The MINERνA Collaboration

The MINERνA collaboration currently consists of 58 nuclear and particle physicists from 13 universities in four countries and two US national laboratories (FNAL and Jefferson Lab). The collaboration members are mostly of senior scientists, teaching or research faculty; however, as our prototyping program ramped up in summer 2004, the number of active students and postdocs on the experiment has increased to six and ten, respectively. The collaborating Universities have a strong record of student training and education, as detailed in Section 3. As construction begins, the collaborating Universities expect to recruit more students at the graduate and undergraduate level, and commit more postdocs to construction and operation of MINERνA.

Results of Prior NSF Support at the Proposing and Sub-Awardee Institutions

Rochester: Although the group is primarily funded by DOE, the group receives support from NSF grant PHY-0242483 ("REU site in physics and astrophysics at Rochester", 7/1/03-present, \$366,008 to date), which supports involvement of undergraduates in the department's research programs, and CAREER award PHY-0134988 ("Precision studies of the top quark and muon telescopes for high school classrooms", 7/1/2002-present, \$193,000 to date), which supports the Rochester PARTICLE outreach to twenty-five area teachers and over 400 of their students in classroom-based cosmic ray experiments. Co-PI Bodek's achievements in studying the structure of the nucleon were recently recognized with the 2004 W.K.H. Panofsky Prize in Experimental Particle Physics, awarded by the APS. Among other efforts, the co-PIs have been involved in SLAC E-140, CCFRR, AMY, FNAL E-53, SLD and NuTeV. They are currently working on CMS, CDF, T2K, MINERνA and the supporting JUPITER (E04-001) program at JLab. Collectively, the co-PIs has supervised 27 postdocs, 33 Ph.D. students, and 38 REU students.

Hampton: Hampton's group is funded under NSF award 0400332 ("Transition to a Quark-Gluon Description of the Nucleon"), in the amount of \$597,290. This award began in September 2004, but continues over a decade of NSF support through base grants, three MRIs, a successful CREST program, and a CAREER award. Hampton also boasts an NSF-supported Physics Frontier Center focusing on elementary paticle physics. In the last three years, the group published 49 papers in refereed journals, with 18 in *Physical Review Letters*. The group presented 50 invited talks at international conferences and seminars, and had a leadership role in the organization of 12 conferences and workshops, two directly sponsored by Hampton. The faculty are spokespersons for 12 approved experiments at JLab. duality, a focus subject for the group since back-to-back, top-cited PRL publications in 2000 verifying this interesting phenomenon. Hampton University, as an historically black college, is a leader in minority education, having doubled the number of African-American physics doctorates awarded in 2001 and 2002, according to AIP statistics.

William & Mary: The William & Mary group is supported by start-up funding through FY05. Since inception in 2003, the group's research has produced one paper for peer-reviewed publication and trained one graduate student, three undergraduates, and one postdoc. The PI was previously Fermilab project manager for MINOS far detector installation and commissioning, as well as detector plane prototyping, magnets, and co-PI for Soudan Underground Laboratory operations in FY 2001-03.

2 Detector Design, Development and Construction

This section describes the MINERνA detector, summarizes its capabilities, and discusses the different construction subprojects to be supported.

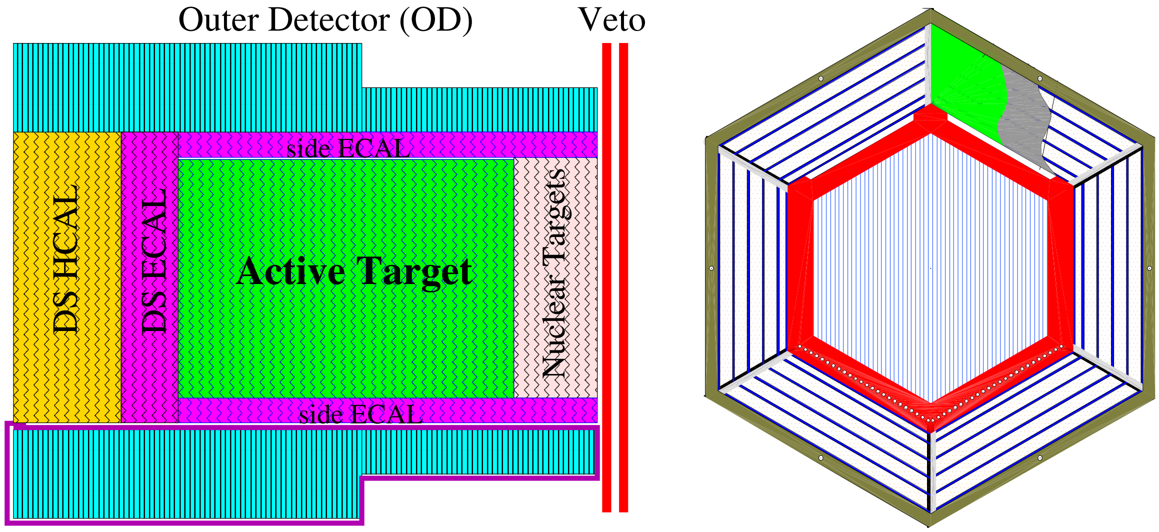


Figure 5: Left: A schematic side view of the full MINERνA detector with sub-detectors labeled. The neutrino beam enters from the right. Right: A slice through the active target region of the detector, showing the Inner Detector (blue), side ECAL (red) and surrounding outer detector.

2.1 The MINERνA Detector

To meet its physics goals, MINERνA must break new ground in the design of high-rate neutrino experiments. With final states as varied as high-multiplicity deep-inelastic reactions, coherent single-π^0 production and quasi-elastic neutrino scattering, the detector is a hybrid of a fully-active fine-grained detector and a traditional calorimeter [1]. Its essential features are described here.

MINERνA is composed of several sub-detectors with distinct functions in reconstructing neutrino interactions. The fiducial volume for most analyses is the inner "Active Target" shown in Figure 5, where the only material is the sensitive scintillator strips themselves. The scintillator detector does not fully contain events due to its low density and low Z, so the MINERνA design surrounds it with sampling detectors. In these sampling detectors, scintillator strips are intermixed with absorbers. For example, the side, upstream (US) and downstream (DS) electromagnetic calorimeters (ECALs) have lead foil absorbers. Surrounding the ECALs are the US and DS hadronic calorimeter (HCAL) where the absorbers are steel plates. The US ECAL and HCAL also serve as the heavy nuclear targets of lead and iron for the experiment. On the sides, the outer detector (OD) plays the role of the HCAL; in addition, the OD is a magnetized hexagonal toroid that will focus and bend muons, allowing a momentum measurement for large-angle muons which exit the detector. Upstream of the detector is a veto of steel and scintillator strips to shield MINERνA from incoming soft particles produced upstream in the hall. Downstream of MINERνA is the existing MINOS near detector, which will measure the energy of muons which do not exit through the OD.

The core active element will be extruded scintillator strips readout *via* wavelength-shifting fibers, similar in concept to the recently commissioned K2K SciBar detector[33]. Scintillation light will be recorded by multi-anode photomultiplier tubes (MAPMTs) (Hamamatsu R7600U-00-M64), connected to the wavelength shifting fibers *via* an optical cable system and housed in light-tight "optical boxes" mounted atop the OD.

For construction and handling convenience, a single plane of MINERνA, shown in Figure 5, incorporates the inner detector, side ECAL absorbers and the OD "picture frame" as well as an outer picture frame support structure. Groups of four planes (or two planes in the upstream veto region) are ganged together into modules. There are three distinct orientations of strips in the inner detector, offset by 60°, and labeled X, U, V. Each module of MINERνA has two X layers to seed two-dimensional track reconstruction, and one each of the U and V stereo layers to identify and reconstruct three-dimensional tracks.

For front-end digitization of the MAPMT signals, a design based on the D0 TRiP ASIC [34] has been developed and tested at FNAL (see Section 2.2). MAPMTs will be directly mounted on the front-end boards (which also include a Cockroft-Walton high-voltage supply for the tube) to reduce input capacitance to the TRiP amplifiers. Both the pulse-height and time (for identification of strange particles and muon decays) of each hit will be digitized. Up to four hits per spill may be buffered. MINERνA will run with a simple trigger gated by the NuMI beam, since event rates are low enough to simply read out every hit after each spill. Digitized signals will be collected by custom VME readout controllers through LVDS chains of twelve front-end boards and transferred to the data acquisition computer over a PCI-VME bridge. Slow control messages will also be exchanged with front-end power supplies over the LVDS readout chains. Data will ultimately be copied to permanent storage on the lab network.

In addition to electrical and mechanical engineering support, FNAL has committed to provide all modifications needed to accommodate MINERνA in the experimental hall, including power, cooling and ventilation upgrades, the magnetic coil and associated power supplies for the OD toroid, and a safety system.

2.2 R & D Results

In Summer 2004, the collaboration began an extensive R&D program in the following areas:

- Testing of triangular scintillator extrusion die
- Development of the readout electronics and creation of a prototype front-end digitizer board (FEB)
- Test of the FEB and scintillator system in a "Vertical Slice Test" (VST)
- Developing a scheme for the mechanical support of the planes of iron and scintillator bars
- Constructing and testing a full module (*XUXV* views) inner/outer detector prototype

Significant progress has already been made on the first three items, as discussed below. Preparations for the remaining tasks are underway.

Triangular scintillator prototypes have been produced using the NICADD/FNAL extrusion facility. Bars of the design dimensions have been successfully extruded, and a $\sim$1.5 mm hole through the center, for fiber insertion, has been integrated into the process. These test bars were used in the VST described below.

A 16-channel FEB prototype, based on the TRiP chip, was designed and tested at FNAL. The essential elements are a TRiP chip (providing discimination, shaping, and an analog pipeline), high- and low-gain 10-bit ADCs, TDCs with 1.5 ns least-count, and an FPGA controller. Readout to the parallel port of a PC can be internally or externally triggered. On the bench, the board achieves the charge and timing resolution necessary for MINERνA.

To test the scintillator, FEB and readout scheme, a small plane of the triangular bars were constructed at FNAL. Fibers from the bars were attached to a MINOS Near Detector M64 MAPMT housed in a MINOS CalDeT PMT box. The output of the PMT was connected to the input of our FEB prototype. The trigger for the readout of the board was either generated internally or through a set of trigger scintillator paddles to tag cosmic-ray muons. Tests of both these modes of operation proved successful. The noise level, integrating over 10 μsecond (NUMI spill time), was $<$2 fC. This is much less than the expected charge of 130 fC from a single photo-electron using our expected operating HV for the PMTs. Both high and low ADC channels were tested and determined to function as expected. Using a blue LED flasher to excite the green fiber we were able to observe the single PE peak using this setup. We are in the process of determining the light yield from a single scintillator layer using cosmic ray-muons. We have just begun to study the timing and spatial resolution for these muon, including the effect of charge-sharing between neighboring strips.

To summarize, in only $\sim$6 months, we have designed, constructed and successfully operated a prototype of our proposed readout scheme. Timing and light yield studies will continue in the months ahead, along with work on mechanical issues related to the construction of the full detector.

2.3 Performance of MINERνA

With the low mass design allowed by the high intensity NuMI beam, MINERνA's response to single particles for exclusive final state identification is more similar to a bubble chamber than to previous high-rate neutrino detectors. MINERνA's performance has been studied extensively in a hit-level simulation, including the photostatistical effects of light collection, a realistic Kalman filter reconstruction package for track and vertex fitting, and particle identification. We base physics sensitivity studies on the results of this simulation.

The fully-active region of the detector has excellent performance for tracking and identification of single particles in the final state, including low-energy recoil protons from low-Q^2 $\nu n \rightarrow \mu^- p$ reactions. Charge sharing between adjacent triangular strips allows excellent spatial resolution. For μ^- from quasi-elastic interactions, the expected hit resolution per detector plane is ~ 3 mm. Fitted tracks from such muons have typical impact parameter and angular resolution of ~ 2 mm and < 9 mrad (Figure 6). Using the (typically short) reconstructed proton track and the muon track from quasi-elastic events, RMS vertex uncertainties of 9 mm and 12 mm are measured in the coordinates transverse and parallel to the beam direction, respectively.

Measured energy loss (dE/dx) is an excellent tool for particle identification in MINERνA. For tracks which stop in the inner detector, the charge deposited near the end of the track (corrected for sample length) can be compared with expected curves for $\pi^\pm$, $K^\pm$ and protons. Figure 6 illustrates the probability of misidentification by plotting the difference $\Delta\chi^2$ between the correct χ^2 (for the particle's true type) and the smallest of the two (incorrect) other particle hypotheses. With this naive dE/dx analysis, we correctly identify 85% of stopping kaons, 90% of stopping pions, and $> 95\%$ of stopping protons.

With the surrounding ECALs for containment, MINERνA's π^0 reconstruction capabilities are excellent. This is essential, since π^0 are a major source of background for ν_e appearance oscillation experiments. As shown in Figure 7, MINERνA's low density and high granularity make it an excellent photon tracker, able to accurately reconstruct the vertex and kinematics even for coherently-produced π^0 with no accompanying charged tracks. Kinematic reconstruction allows coherent and resonant π^0 production to be distinguished. In Figure 8, the true and reconstructed angular distributions are nearly identical, allowing coherent π^0 production to be extracted by its characteristic forward peak above the more isotropic resonant interactions.

2.4 The Proposed MINERνA Fabrication Project

To provide the granularity required to identify final-state particles in low-energy neutrino interactions, and to accurately track photons for π^0 reconstruction, the number of channels in MINERνA must be large. In addition, MINERνA must be large enough to contain final state particles. These consideration have led us to a design which has at its center a fully-active scintillator strip detector for tracking and energy resolutions, surrounded by calorimeters. The front calorimeters which double as nuclear targets and downstream ECAL and HCAL use the same planes of scintillator strips. As shown in Figure 5, these scintillator planes are hexagonal in shape, with a minor diameter of approximately 210 cm. Each plane consists of 128 triangular inner detector extrusions arranged in a plane, and the hexagonal symmetry allows the strips to be oriented in one of three directions to allow the tracking to reconstruct in three dimensions.

To jump-start the construction of MINERνA this proposal seeks to fund the construction of the inner detector planes for the MINERνA fully active inner detectors and calorimeters. The current design has a total of 196 such planes, 120 that comprise the fully-active inner detector, 36 that are part of the nuclear targets and 40 that provide position sensitivity and muon tracking in the downstream calorimeters. The total number of scintillator strips in these planes is 25088, the total mass of extruded scintillator is 13.1 metric tons, and the total length of fiber required inside the scintillators, the assemblies and in the 3136 clear fiber cables is 99 kilometers, 68 of which are wavelength shifting (WLS) and 31 of which are clear.

Fabrication of the inner detector planes will be a coordinated effort among the three institutions in the proposal and Fermilab. The sub-projects, scintillator bar production, WLS fiber production, scintillator plane assembly and clear fiber cable production are briefly summarized below; more detail can be found in the budget descriptions for the proposing and sub-awardee institutions. When completed, the planes will be shipped from the Virgina factories to Fermilab for installation in MINERνA detector modules, an installation process not supported by this proposal.

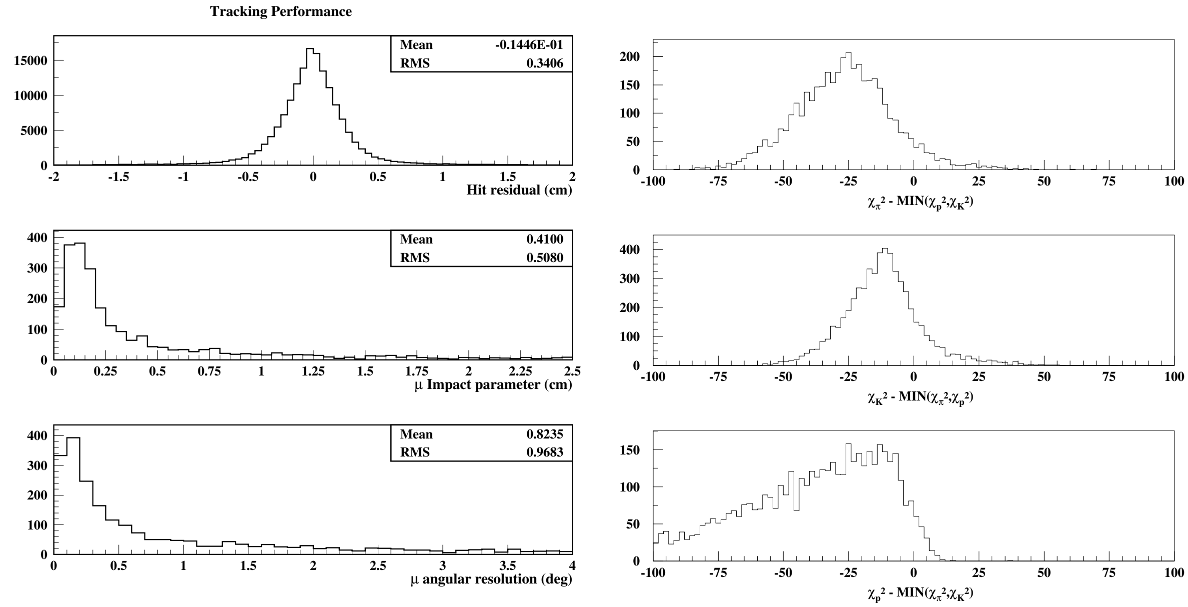


Figure 6: Left: Coordinate resolution, impact parameter and angular resolution for muons produced in CC reactions. Right: the $\Delta\chi^2\ dE/dx$ estimator for simulated charged pions(top), kaons(middle) and protons(bottom) stopping in the inner detector. Tracks with $\Delta\chi^2 < 0$ are correctly identified.

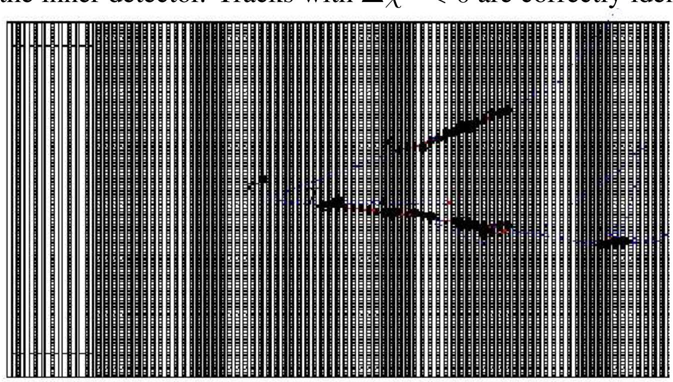


Figure 7: A simulated NC coherent π^0 production event in MINERνA (for clarity, the OD is not shown). The π^0 decay vertex can be determined accurately by extrapolating the two photons backward. Note that both photons pass through a number of planes before beginning to shower, distinguishing them from electrons.

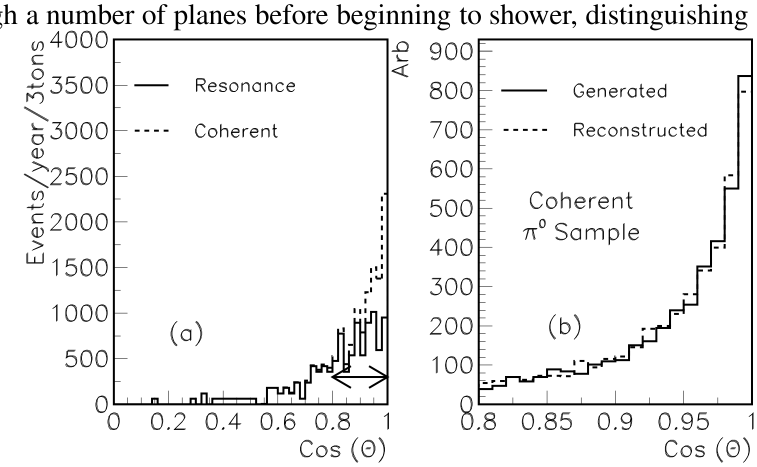
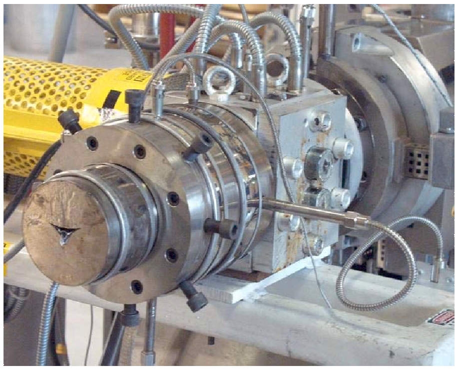


Figure 8: Angular distribution of NC single-π^0 sample. At left, all events passing the cuts described in the text, with resonant and (forward-peaked) coherent contributions. At right, a close-up of the forward region compares true and reconstructed π^0 angles, demonstrating MINERνA's excellent angular resolution.



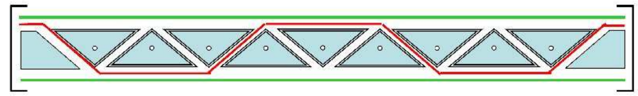


Figure 9: Left: Die developed to produce scintillator bar prototypes for MINERνA's vertical slice test, mounted to the front of the NICADD extruder. Right: Schematic cross-section of an ID plane, or hex, assembly. The triangular scintillator strips are blue, the outer skins green, the inner web is red, and the outer edge seals are black..

2.4.1 Scintillator bars (Rochester)

Scintillator strips will be produced using the NICADD-owned, Fermilab resident scintillator extrusion facility. The facility has produced extruded scintillator for a number of high- and medium-energy experiments; it has proved to be significantly more cost-effective and responsive to prototyping than industrial competition. The first step of the project is installation of a co-extruder required to add a diffusively reflective outer coating to the bars which requires the procurement lead time plus one month installation time. Next, we will develop and tune a die (a prototype MINERνA triangular die is shown in Figure 9) to control the cross-section and fiber hole in the extrusions. Fabrication of the die by the vendor will be done in parallel with the co-extruder, and two months are alloted for tuning the die. Finally, the extruder produces the bars (67 days factory time), and we ship them to the Virgina plane assembly factories.

2.4.2 WLS Fiber Preparation (Rochester)

WLS fibers will be ordered from Kuraray and shipped to Fermilab. After fiber qualification tests carried out by Rochester physicists, FNAL technicians (not supported by this proposal) will cut the fibers, polish one end and add a vacuum deposition mirror. The prepared fibers will be shipped to the Virgina scintillator plane factories for installation.

2.4.3 Scintillator plane assembly (Hampton and William & Mary)

Hampton and William & Mary, located less than 20 miles apart, will partner to assemble the scintillation planes for both the inner and outer detector. A plane assembly consists of scintillator bars, outer light tight skins and a supporting web as shown in cross-section in Figure 9. Fibers are brought out one end in a routing manifold which ends in the connectors used below in the optical cables. Both universities will procure the materials needed for the assemblies including fiber routing manifolds, skins, internal webs, adhesives, and consumables needed for this assembly and testing. During assembly, the scintillator will be cut, glued to skins and webs, and assembled with the fiber routing tray into planes. Fibers will be inserted, dressed, and connectors polished. Bad fibers and light leaks will be corrected during the assembly process. Completed planes will then be shipped (in custom-fabricated boxes) to Fermilab for final assembly into detector modules.

2.4.4 Optical cables (Rochester)

Rochester will develop clear fiber optic cables to carry the light from the WLS fibers which end at the detector edge to the light-tight boxes containing the PMTs. One light-tight cable will run from eight WLS fibers to an optical box. We will construct 8-fiber cables using a custom spring-loaded snap-in connector developed by Fujikura (formally DDK). The project includes wrapping fiber bundles into cables, gluing fibers into cable ends and polishing the cables. The work also includes construction of a cable-testing apparatus to check transmission, light leaks and cross-talk.

3 Broader Impact of MINERνA and the Inner Detector Project

MINERνA is well-suited to ensure broad impacts and educational opportunities with its construction and physics program. These impacts can be demonstrated by the collaborators' records in graduate training, their involvement in and commitment to undergraduate research, the key role of an historically black institution, and finally a dedicated education and public outreach (EPO) program proposed as part of this project.

Graduate research is integral to MINERνA. The sheer breadth of MINERνA's physics program is a cornucopia of Ph.D. thesis topics, and the experiment is small enough (by particle physics standards) that individual students can make significant contributions. The construction lead time is short, so students can experience building and operating the experiment as well as physics analysis. Most of the collaborating universities support significant numbers of graduate students in experimental nuclear and particle physics.

MINERνA collaborators also share a commitment to undergraduate student training in the research environment. The majority of our institutions (Irvine, Hampton, James Madison, Rochester, Rutgers, and Tufts) will support undergraduates directly as part of this proposal. Several are active NSF REU sites (Hampton, Pittsburgh, Rochester) with a record of training undergraduates in particle and nuclear physics research. James Madison University is a non-Ph.D.-granting institution, whose undergraduates would not be exposed to research in particle and nuclear physics without opportunities like this project. At least half a dozen students have already contributed to the design of MINERνA and gained hands-on research experience in our vertical slice test, and that number will increase many-fold once construction of the detector begins.

One of the largest contributors to our fabrication effort, Hampton University, is an historically black institution. In 2001, the HU Physics Department graduated over 70% of the African-American PhDs nationally [35]. The first two nuclear physics PhD's to African-American women from an HBCU were awarded by Hampton in 2001 and 2002. Through Hampton's central involvement, starting with a key construction role engaging undergraduate and graduate students, this proposal will provide state-of-the-art training for young African-American researchers, who are vastly under-represented in particle and nuclear physics. These opportunities address a national need for diversity in the educational pipeline and growth in programs that can attract African-American students into science to address the troubling fact that African-Americans currently make up less than 10% of the undergraduate science population, under 5% of the graduate population, and less than 2% of the doctoral majors nationally [36].

Finally, to ensure educational impact of MINERνA beyond the collaborating universities, we have conceived a program in EPO to complement the construction effort. The simple, relatively inexpensive, and modular design of MINERνA and the striking, intuitive appearance of particle tracks passing through it, lend themselves as a vehicle for teaching and demonstrating the principles of physics on which it relies. The uncanny properties of neutrinos provide a perfect "hook" to engage the curiosity of students and the general public. Our program will have three components:

3.1 Mini-MINERνA

Rochester will host a team of undergraduates, a secondary school teacher and students, and a graduate student for one summer to develop a small version of an extruded scintillator strip detector (Mini-MINERνA) to demonstrate the detection of cosmic rays. To simplify the data acquisition, mini-MINERνA will not use the MINERνA MAPMTs and front-end electronics, but rather a multi-stage image intensifier connected to a network-attached camera for data acquisition. The teacher and students will be recruited from the base currently involved with the Rochester PARTICLE program [38], and initial use of the Mini-MINERνA detector would focus on serving as a demonstration apparatus for classroom visits as part of PARTICLE. Equipment funds are requested for the image intensifier and camera, but other materials for the project as well as modest technician and machining support will be obtained from scrap materials and existing technical staff supported in the process of constructing MINERνA.

3.2 Mobile-MINERνA

Taking "Mini-MINERνA" one step further, we will build five additional miniature cosmic-ray detectors (each consisting of several planes, with 64 strips total) based the multi-anode PMTs used in the detector and prototype digitizer boards interfaced to desktop or laptop computers. We will distribute these portable "Mobile-MINERνA" detectors among the participating institutions and laboratories for demonstrations to enrich on-going outreach and educational activities. One of the MINERνA collaborating institutions, UC-Irvine, for instance, leads an NSF-supported "assemblies" program of K-12 outreach to predominantly Latino and African-American schools in the Los Angeles area. A Mobile-MINERνA detector could be integrated with the project's Modern Physics and Optics demonstrations and reach dozens of public schools every year. UCI also hosts popular and well-attended open nights at the campus observatory, where the detector could demonstrate cosmic-rays and introduce visitors to neutrino physics. Other collaborating institutions, of course, sponsor similar activities. The detectors could also be used by the Fermilab and JLab Visitor's Centers, and as classroom lecture demonstrations at universities. As with Rochester's Mini-MINERνA project, most components for the portable detectors can be collected from material left-over in construction.

3.3 MINERνA Interactive

Supporting the first two efforts, and reaching out further over the Internet, we will add a rich online dimension, MINERνA Interactive. This portal will offer an array of engaging activities and information to students, educators, and the lay public. We will provide real-time, interactive display of the MINERνA datastream, and downloadable Windows versions of the Nuance neutrino physics and MINERνA detector simulation programs featuring simplified graphical interfaces and built-in educational content. Hotlinks in the programs, and on the website, will bring up supporting information on physics topics ranging from basic optics to elementary particles. We will also offer installation CD-ROMs by mail to teachers, with suggestions for incorporating the material into a lesson plan at different grade levels. Several of our collaborating institutions, including UC-Irvine and Rochester, plan to use existing operating funds and REU programs to support student labor to establish the website, create user-friendly front-end code for our simulations, and program the real-time network interface between the server and the online data acquisition system.

4 Project Management Plan

MINERνA has a mature detector design and construction and installation plan and has received Stage I (physics) approval from Fermilab. Technical feasibility of the active inner detector elements have been validated through the vertical slice test described in Section 2.2. The technical design and construction plan went through a successful Fermilab internal ("Temple") review in January 2005. This proposal seeks to fund only a portion of MINERνA, and therefore successful completion of the goals of this proposal relies additional funding beyond this proposal. In this section, we summarize the costs and schedule of the MINERνA construction and installation project, detail the management plan in place to realize the project, and describe the proposed interaction between this proposal and other sources of funding.

4.1 The MINERνA Construction and Installation Project

Table 1 lists the costs and institutional responsibilities associted with all level 2 WBS elements of the project. In most cases costs are estimated either directly through vendor quotes (with PMTs, fiber, and steel being the cost drivers), or are extrapolated from direct experience projects with similar detector items projects such as MINOS or the CMS HCAL. Costs are escalated over these direct estimates to allow for unforeseen project items, cost escalation from vendors and the possibility of currency or raw materials fluctuations. Costs for each subproject are divided into materials and services (M&S), salaries, wages, and fringe (SWF), engineering and design. F&A costs are absorbed into each sub-category. (Note that the budget breakdown here is not identical to the budget pages; for example, the University of Rochester puts all sub-projects into fabrication tasks in their fully-costed shop where they are categorized as equipment and escape indirect costs.)

We have integrated the estimated completion times for various tasks into a linked schedule of sub-projects for construction of MINERνA. This is *not* a resource-loaded schedule, although some resources, e.g., the scintillator extrusion facility, have been leveled in this schedule. Because most of the construction takes place a different universities under independent personnel, we don't foresee a great deal of coupling among

Project	WBS	M&S	SWF	Eng. & Design	Total
Scintillator Extrusion & Planes	1.1	$1,240,739	$1,394,943	$47,911	$2,683,594
Clear Fibers and connectors	1.2	$445,864	$369,740	$68,960	$884,564
PMTs, boxes, testing	1.3	$1,263,124	$417,112	-	$1,680,236
Electronics, DAQ and Controls	1.4	$574,730	$19,714	$459,358	$1,053,803
Frame and absorbers	1.5	$882,105	-	-	$882,105
Module assembly	1.6	$154,666	$512,932	$157,964	$825,562
Coil	1.7	$208,600	-	$91,000	$299,600
Installation Preparation	2.1	$57,000	$184,400	$199,400	$440,800
NuMI Hall Infrastructure	2.2	$142,800	$150,100	$50,000	$342,900
Detector Installation	2.3	-	$405,900	-	$405,900
Total		$4,969,628	$3,454,841	$1,074,594	$9,499,064

Table 1: WBS categories and costs for each Level-2 sub-project

the projects at the level of resources. Rather that coupling is at the level of *deliverables* which is where the links in this schedule are drawn.

Throughout this project, the estimated time required to complete tasks is based primarily on direct extrapolations from past similar projects. Where those are not available, we have relied on time-motion estimates wherever possible. For delivery of products from vendors, we rely on delivery dates from recent quotes. Because we rely on specialty materials or sole source items from individual vendors (fibers from Kuraray, MAPMTs from Hamamatsu and special steel), our schedule may be vulnerable to fluctuations from this source. In part for this reason, the bulk of our purchasing is completed as soon as possible and is heavily front-loaded into year one of the project.

Finally, at several points in the project we rely on already obtained or soon to be realized milestones from our R&D program. For example, we expect to complete development of the triangular inner detector extrusion die and the second prototype front-end board design before the start of the project.

Our current schedule calls for completion of the module assembly and mapping 24 months after project start. (We have proposed that the project start June 1, 2005; so the conclusion would be the end of May, 2007.) Several tasks independent of the module production, such as the installation of PMTs and front-end boards in the PMT boxes continue approximately one month beyond.

The critical path for completion and installation of the detector is the initial production of scintillator bars for the inner detector, completion of the inner detector planes, and the subsequent installation of these planes into modules and then into the NuMI Hall. Near the critical path are construction of the clear fiber cables and the PMT dark boxes, the latter of which is not supported in this proposal.

Summary of Deliverables of the Inner Detector Plane Construction (this proposal)

Item	Quantity	Institution	Initial Production	Final Production	Delivered to
Scintillator Bars					

Table 2: Deliverables supported by the development funds from this proposal

Items in this proposal correspond to a large fraction of the WBS items 1.1 and 1.2 shown in Table 1. Deliverables, quantities and scheduled dates for first and last shipments (assuming a June 1, 2005 project start) are shown in Table 2. Note that deliverable quantities include spares. The detailed schedule for the items supported in this proposal is shown in Figure 10.

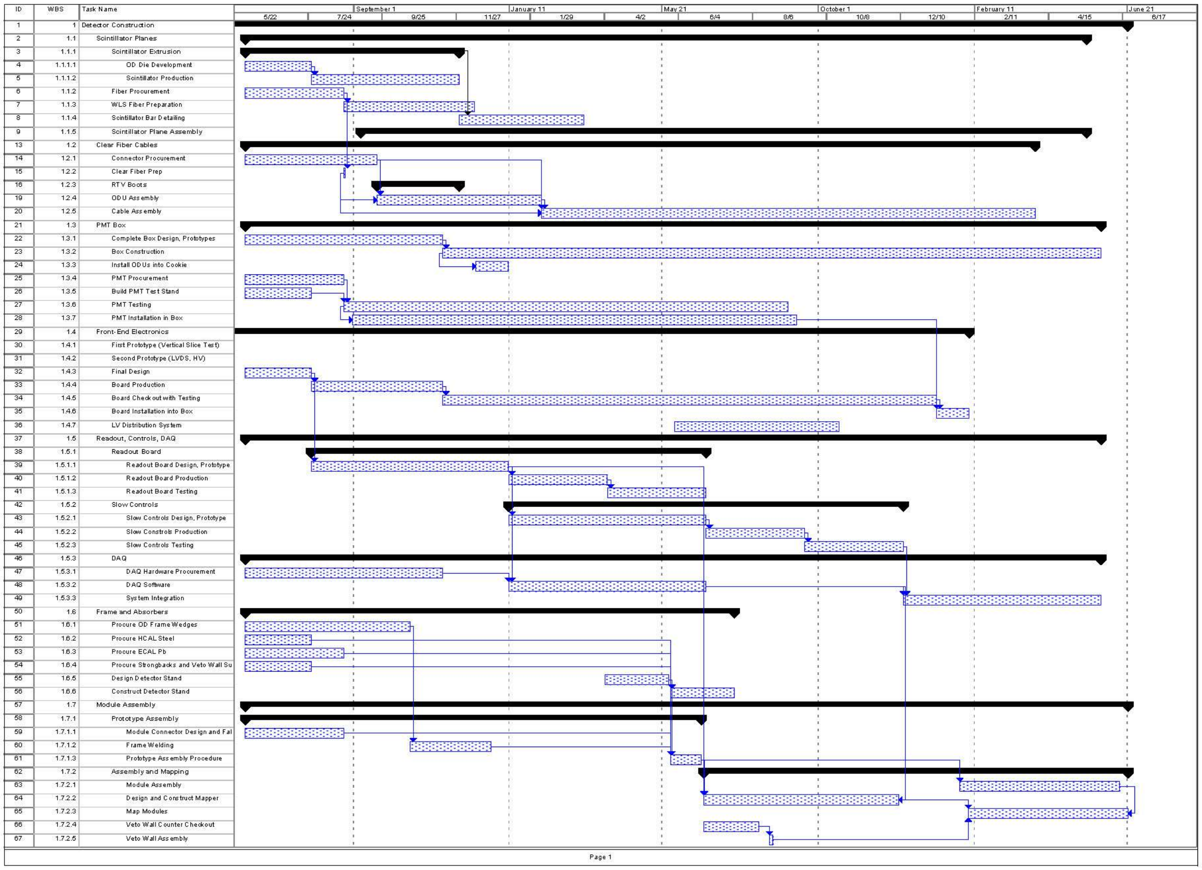


Figure 10: Breakdown of the MINERνA construction schedule for items supported in this proposal

4.2 Management of the MINERνA Project

To ensure effective organization and management of this project, which is distributed across many universities and the host lab, it will be coordinated by a Fermilab-resident project manager. The project manager will report to a Project Management Group (PMG) established by the Fermilab Directorate which will consist of of representatives from the Fermilab Directorate, Business Office, and Particle Physics Division among others. The project manager's responsibilities will include quarterly progress reports on milestones and expenditures to Fermilab, *via* a project management group (PMG), and to all funding agencies supporting the project. Universities will appoint a local project liaison who will report their progress and expenditures within a work breakdown structure (WBS) maintained by the project manager. University sub-projects will be run by Level-2 managers, who will normally be a PI in a collating university group on that project. Where needed, there will also be Level-2 (co-)managers at Fermilab to oversee FNAL installation and safety responsibilities.

For proposals submitted by universities, such as this one, funding will flow directly to the universities. To ensure that fiscal oversight is maintained, the Level-2 managers will collect and report the progress of each sub-project (work scheduled, work performed, costs and variances) regularly, allowing the project manager maintain a close financial watch on the project. We propose that the project manager should work directly with the funding agencies to determine milestones and conditions for the release of funds to each university. This should include a procedure for designating a portion of the proposed cost as contingency, based on the cost justification presented at the Fermilab review to approve baseline project costs (a future "Temple" review), and for developing a procedure for releasing that contingency to the universities only as required. Similar interactions between the project manager and Fermilab will be required to manage and track Fermilab expenditures.

This project management plan is similar to past collaborative Fermilab/university management plans used by several smaller Fermilab experiments.

Once commissioned, data obtained by MINERνA will be shared by the entire collaboration. In addition, the close proximity of the MINOS experiment's near sampling detector may make it desirable to provide MINERνA data to MINOS, and vice versa, for events extending from MINERνA into the MINOS detector. We have maintained close communication and cooperation with MINOS throughout design of MINERνA, and have ensured that this exchange of data is technically possible with our design.

Operation and support of the completed detector will be the responsibility of the MINERνA Collaboration and the host lab, FNAL, as appropriate. Personnel to provide these tasks, as well as analyze the data, will be supported from operating grants of the collaborating institutions and Fermilab.

4.3 Funding the Entire MINERνA Project

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